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Multifactor Method for Evaluating the Effectiveness of Wood Fire Protection

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Abstract. The problem of using fire-resistant materials for wooden building structures is to ensure their stability and durability when operating in atmospheric conditions, when it is possible to wash out flame retardants and lose fire resistance. The purpose of this study is to identify the indicators of fire hazard of wood, fire-proof coatings and the effect on them of the heat-insulating layer of coke formed, which allow justifying the effectiveness of the fire-resistant coating under the influence of temperature. The study used a comprehensive research method, which consisted in determining the fire-hazardous properties of fire-proof wood and methods for determining the operational properties of wood fire protection. It was found that upon applying a coating based on alkyd-polyurenitan varnish, due to the polymer film formed on the wood surface, the permeability of flame-retardant components decreases. Tests of fire-hazardous features of wood protection from fire have shown that the coating swells under the influence of heat flow and contributes to a significant heat-insulating layer of coke, which prevents oxygen from reaching the wood and, accordingly, hot temperature, which can ignite the wood. In general, the effectiveness of wood protection from fire shown that wood protected from fire belongs to hard-to-burn materials that slowly spread flames on a surface with low smoke-forming ability. The practical value of this paper lies in the fact that the obtained method for identifying the features of wood protection from fire, comprises determining both atmospheric and thermal properties, and allows establishing the operating conditions of fire protection and the use of products and building structures made of wood of a wide range of uses

Keywords: protective equipment, weight loss, wood surface treatment, flame retardant leaching, polymer shell

Introduction

The scope of use of wood and its structures in construction is broad. Considering the fact that these materials and wood products constitute the main combustible materials and conductors of flame propagation, the safety of wood ignition places high demands on fire protection, as well as on the quantity and quality of fire-proof materials. The effectiveness of fire protection of objects for various purposes is increased with the use of fire-proof wood, which meets the requirements of regulatory documents [1; 2].

For fire protection of wood, water-soluble compositions on an inorganic basis are used, forming a ceramic layer on the surface under the influence of temperature and releasing water, and for effective fire protection they require more application [3]. Today, for the fire protection of wood, a coating capable of forming a heat-insulating layer of foam coke, which thermally insulates the surface of the wood, has been widely used on the surface of the building structure [4]. During the swelling of the composition, the components decompose with simultaneous endothermic decomposition of flame retardants and gas-forming agents, which facilitates a dense layer of foam coke, thereby creating fire-resistant properties of the coating [5]. However, with prolonged exposure to elevated temperatures, which reaches over 1,000°C with a developed fire, individual coatings gradually burn out and to increase efficiency, require an increase in the amount of substances forming a more stable layer of foam coke [6]. This is precisely what determines the need to develop research in this area.

The specific feature of modern fire protection of building structures from fire is to create the necessary layer

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of foam on the surface, which thermally insulates the high fire temperature of over 1,000°C and creates a layer of foam on the wood surface, thereby slowing down the heating of the material and transferring wood to the group of hard-to-burn materials. They constitute complex mixtures of organic and inorganic substances described by high foaming ability. But there is no information on how they are used when atmospheric fluctuations change, in particular, temperature and humidity.

The description of the properties of intumescent coatings is described in [7]. This allows evaluating the conducted studies on thermal stability, where the thermophysical model is considered. But issues related to resistance to atmospheric fluctuations when used in outdoor conditions are still unresolved.

The effectiveness of using flame retardant coatings based on organic components is shown in [8], where flame retardants based on polyphosphoric acids and gas-forming agents can change the conditions for the development of the insulating layer of foam coke. The effect of thermal modification, as well as the ability to protect, revealed by the characteristics of combustion, such as weight loss, burning speed, flame spread, was investigated, but no information was provided on how the chemical changes occurring under the influence of these factors take place. Therefore, it becomes necessary to investigate the conditions for reducing thermal conductivity and determine the conditions for the formation of foam coke.

In [9], the behaviour of wood impregnated with organo-inorganic flame retardants is described, the results of research and testing of which were aimed at investigating the technology and compositions that combine fire resistance, thermal conductivity, and manufacturability of protective coatings. A modified binder made based on liquid glass is used as the main part of the developed compositions. The study describes two types of compositions. The first is a porous heterogeneous structure made based on the authors' technology of two-phase structuring and thermal pore spacing. This composition is intended for the manufacture of moulded products. The second composition is used for the manufacture of fire-retardant coatings by monolithic method. In the study [10], methods for evaluating the response indicators of wood to fire treated with flame retardants based on organophosphate substances were discussed. Such wood was used as the facade of buildings, considering the deterioration of ageing. The fire resistance characteristics of wood were investigated, and it was found that the first indicators worsened during the fire response test by more than 12%.

In the paper [11], the effect of modification, as well as flame retardant ability, was investigated, revealed by such characteristics of combustion as weight loss, burning speed, etc.; however, the issues regarding the manifestation of the joint action of the components remain unexplained. The study [12] was conducted to solve the question of the application as a coating containing many fire-resistant compositions from the sludge of industrial effluents. The coating formula was optimised using a response surface methodology based on a central composite design. During the fire resistance test, this sample shows the lowest reverse surface temperature of the sample (only 163°C) among all samples, which indicates excellent fire resistance. Apart from the analysis of fire resistance, the water resistance and thermal stability of fire-resistant coatings are also characterised.

Furthermore, a considerable number of coatings have disadvantages, such as the application of individual components, loss of functional properties with increasing ambient temperature [13]. This indicates that the coating does not always decompose during operation upon temperature and humidity fluctuations.

In [14], the durability of the fire-resistant properties of a transparent fire-resistant coating for a wood structure was investigated using accelerated hygrothermal ageing. The effects of ageing were analysed using morphological analysis and a fire test. The results indicated that after 21 days of ageing, the flame-retardant components gradually surfaced. The coating mostly lost its ability to expand, and the charred layer showed an unstable lamellar structure. The fire resistance of the coating decreased by 43.48% from 23 min to 13 min.

Thus, it was established from literature sources that fire-resistant coatings can be washed out of the wood surface during operation and the parameters that ensure resistance to the loss of fire protection by wood, as well as what affects this process, are not defined.

The purpose of this study was to investigate the compliance of fire-proof wood with both fire-hazardous properties and operational ones.

To achieve this purpose, the following tasks were solved: the specific features of reducing the degree of wood burnout due to temperature exposure to the sample during the application of the coating were established; the operational properties of wood and establishing the compliance of protective compositions were investigated.

The scientific originality of this paper lies in the development of a multifactor method for assessing fire-resistant properties by indicators of flammability, flame propagation by the surface, smoke-forming ability, as well as operational properties as a corrosion effect and fixation of a fire-resistant coating.

Materials and Methods

Research on determining the fire hazard indicators of fire-proof wood was carried out based on the "Fire Safety Testing Laboratory", city of Chernihiv, operational indicators of fire-proof wood were identified at the laboratory at the National University of Life and Environmental Sciences of Ukraine.

The studied materials that were used in the experiment. The study of countering the leaching of a protective agent from wood treated with a fire-resistant composition was carried out on samples of equal-layer wood (Fig. 1).

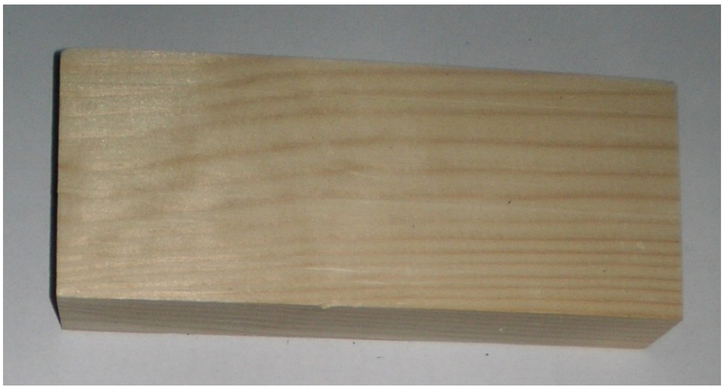

Figure 1. Model samples of pine wood for testing

Samples were treated with a flame retardant for wooden structures ("FAIERVOL-LAK") (Ukraine) in the amount of 580.2 g/m^2; therewith, the thickness of the flame-retardant coating was about 250 microns, which was determined earlier. To increase the water resistance, the samples were covered with a protective finishing varnish "Alkid-Poliuretanovyi Lak" (TM "Kompozyt") (Ukraine) in the amount of 55÷58 g/m^2 [15]. The thickness, respectively, was about 50 microns.

Methodology for determining the properties of samples of fire-resistant wood coating. Studies to determine the compliance of fire-proof wood with the fire-technical classification, namely flammability, flame propagation index and smoke formation, were carried out according tofire safety requirements [1; 2], which are given in the regulatory documentation [16; 17]. To assess the degree of hydrophobisation of wood, a sample of the material is fixed in a test device and exposed to a static layer of water until it penetrates the material (Fig. 2).

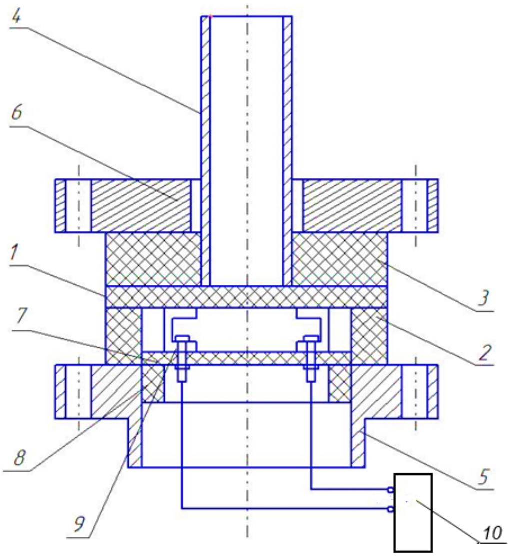

Figure 2. Device for determining the hydrophobicity of fire-proof wood: 1 – test sample, 2, 3 – rubber gaskets, 4 – fluoroplastic pipe, 5, 6 – flanges, 7 – fluoroplastic plate, 8 – ring, 9 – electrodes, 10 – recording device

The criterion for assessing water resistance is the nature of the behaviour of the sample under the action of a static water layer: determination of the increase in the sample after exposure to its surface with water, specific water absorption of the sample, and the degree of hydrophobisation is estimated from the measured values.

In the test setup (Fig. 2), a fire-resistant sample 1 of cellulose-containing material with dimensions of 65x65 mm, a thickness of up to 1.5 mm, untreated and treated, e.g., with a hydrophobic composition, is fixed between rubber gaskets 2 and 3 and sealed with flanges 4 and 5, water in the amount of 200 ml is poured into a fluoroplastic pipe 6 with a diameter of 24 mm. In the lower part of the device, a fluoroplastic plate 7 is installed, which is fixed on one side by a ring 8, and the other touches two electrodes 9 to the reverse part of the sample 1, which are connected to the recording device 10. During the tests, the time of water passage on the return surface of the textile material is recorded, which is evaluated by closing the electrical circuit with fixation on the device.

Characteristics after testing for hydrophobicity of fire-proof wood were determined according to the following coefficient:

$$K_e = 10\left(1 - \frac{\tau_{fp.s.}}{\tau_{h.fp.s.}} \cdot \frac{\upsilon_{h.fp.s.}}{\upsilon_{fp.s.}}\right) \quad (1)$$

where $\tau_{h.fp.s.}$ is the water penetration time of a fire-proof hydrophobised sample; $\tau_{fp.s.}$ is the water penetration time of the fire-proof sample. $\upsilon_{h.fp.s.}$ is the amount of water absorbed by the hydrophobised fire-proof sample, kg; $\upsilon_{fp.s.}$ is the amount of water absorbed by the fire-proof sample, kg.

Determination of the corrosion effect on plates made of flame-resistant coating metals was carried out according to the method [18]. The essence of the method for determining the corrosion effect is to determine the mass loss of a metal plate when interacting with fire-proof wood.

The value of the duration of fire protection of wood was carried out according to the method [19]. The essence of the method for determining the duration of fire protection of wood is to model the diffusion processes of fire-resistant agents artificially and determine the weight loss of fire-resistant wood.

Using the three-factor simplex-central method of planning an experiment in the mathematical environment Statistica 12, statistical processing of the results was performed to determine the weight loss of wood.

The factors of variation were selected as follows: temperature of thermal modification, °C, (factor X_1); amount of coverage, g/m² (factor X_2), the change of which is presented in Table 1.

Table 1. Factors of variation

Factors	Code	Levels of variation			Variation interval
		-1	0	+1	
Number of test cycles	X_1	64	68	72	30
Amount of organo-inorganic coating, g/m²	X_2	350	400	450	10

As the initial parameter (response function), the proportion of destroyed material was chosen, the values of which were recorded on samples exposed to microbacteria.

The experimental planning matrix and its mathematical implementation are presented in Table 2.

Table 2. Experimental matrix and its implementation

Seq. No.	Factors, type		Planning matrix		Response function	
	X_1	X_2	Number of test cycles	Aamount of coverage, g/m²	Y fact.	Y calculation
1	1	1	72	450	8	8.14
2	1	-1	72	350	10	10.54
3	-1	1	64	450	7	6.60
4	-1	-1	64	350	9	9.00
5	1	0	72	400	11	10.33
6	-1	0	64	400	8.4	8.79
7	0	1	68	450	6.2	6.46
8	0	-1	68	350	9.4	8.86
9	0	0	68	400	8.2	8.65
10	0	0	68	400	8.8	8.65
11	0	0	68	400	8.1	8.65

Thus, experimental points with coordinates *+1* and *–1* in a full factorial experiment, where all combinations of factor levels found at the vertices of the hypercube are realised. By writing out combinations of factor levels for each experimental point, a plan for a complete factor experiment of Type 2^3 was obtained, which is showed in Table 2.

Results

The results of studies on the experimental determination of the wood flammability group are presented in Figure 3. It was established (Fig. 3.) that fire-protected wood belongs to construction products of low flammability (F1), and untreated wood belongs to construction materials of high flammability (F4).

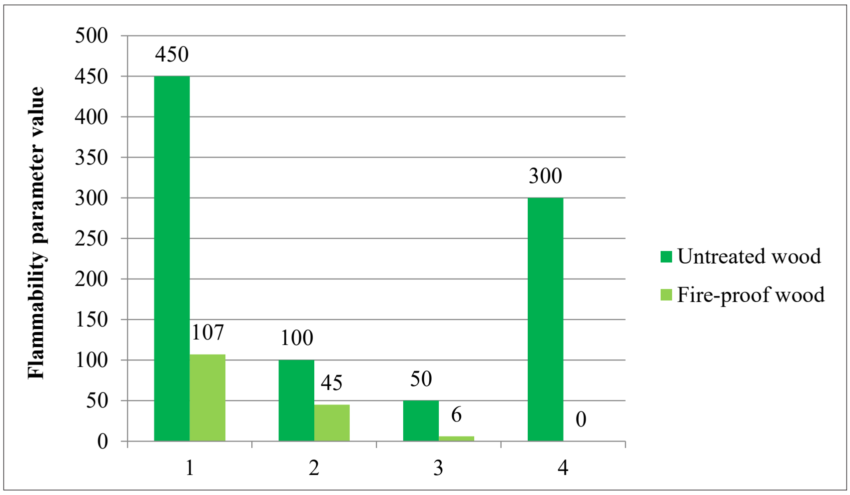

Figure 3. Determination of the flammability group of treated wood): 1 – flue gas temperature (t, °C); 2 – the degree of damage to the samples by length (S_L, %); 3 – degree of damage by mass (S_m, %); 4 – duration of independent combustion (τ, s)

In Table 3 shows the results of determining the flame propagation group by wood. According to the results of experiments, samples of wood with a fire-proof coating are classified as materials that do not spread flames on the surface (RP1), and untreated wood as materials that spread flames on the surface (RP4).

Table 3. Test results for determining the flame propagation group by wood

Wood	Sample combustion time from the start of testing, s	Duration of flame burning of the sample, s	Average value of the damaged part of the sample, mm	Critical surface heat flux density, kW/m²
Unprocessed	36	Over 600	686	4.1
Fire-proof	Missing	Did not occur	39.6	Over 11.0

Figure 4 demonstrates the results of determining the smoke formation coefficient of fire-proof wood. Studies have shown (Fig. 4) reduction of the smoke formation coefficient by more than two times for fire-proof wood samples and their transition from the group of materials with high smoke-forming ability (for untreated samples) to the group of materials with moderate smoke-forming ability (D2).

Figure 4. Results of determining the smoke generation coefficient (D_m, m²/kg) in case of flame burning and smouldering of samples of untreated and coated wood

Studies have shown (Fig. 4) reduction of the smoke formation coefficient by more than two times for fire-proof wood samples and their transition from the group of materials with high smoke-forming ability (for untreated samples) to the group of materials with moderate smoke-forming ability (D2).

Thus, pine wood, which is coated with a fire-proof coating based on organic and inorganic substances ("Faiervol-Lak") with an external coating of one-component alkyd-polyurenitan varnish "Lompozyt", can withstand temperature exposure. According to the fire classification, fire-proof wood belongs to materials of low flammability, a difficult-to-ignite material that does not spread flames on the surface, with a moderate smoke-forming ability.

To assess the degree of hydrophobisation of wood, untreated samples of cellulose-containing materials were first tested. When a hydrostatic column of water acted on the surface (area S=0.00423 m²) of untreated samples, their impregnation with water and intense leakage through the test sample occurred within a time interval of about 300 s. Then the samples were tested, which were treated with hydrophobising agents. During the tests of wood samples protected by a polymer film of the "Gembar" preparation, insignificant impregnation was established for more than 2100 seconds, which considerably exceeds the value of untreated wood by more than 7 times; on the other hand, for samples treated with alkyd-polyurethane varnish, this value increases by more than 42 times (Table 4).

Table 4. Assessment of the degree of hydrophobisation of wood

Samples	Contact closing time when exposed to water τ, s	Amount of water absorbed, kg	Efficiency factor, K
Pine wood without hydrophobiser	306	0.009	–
Pine wood treated with "Gembar" preparation	2122	0.008	8.71819
Pine wood treated with a hydrophobiser based on alkyd-polyurethane varnish	12600	0.001	9.975714

As it was established upon calculating for samples of cellulose-containing materials with insufficient protection of the hydrophobiser, the efficiency coefficient is within 6÷9, and for the protection necessary must be at least 9.5 [20].

The results of determining the corrosion effect of protective agents for wood applied to the sample are presented in Table 5.

Table 5. Value of corrosion destruction of metals in contact with fire-proof wood

Samples	Average specific mass loss rate of a metal plate, $g/m^2 \cdot hour$			
	Steel	Copper	Galvanised tinplate	Aluminium
Fire-proof pine wood without hydrophobiser	0.022	0.146	0.034	0.0025
Organo-inorganic coating with hydrophobiser based on alkyd-polyurenitan varnish	No corrosion detected	No corrosion detected	No corrosion detected	No corrosion detected

As the obtained values demonstrate, copper has the greatest corrosion in contact with flame retardants of an organo-inorganic coating, so this indicator must be considered when designing fire protection. The wood protected by an organic-inorganic coating with a hydrophobiser based on alkyd-polyurethane varnish showed no corrosion. Due to the resulting polymer coating, the yield of flame-retardant components that cause corrosion is considerably reduced.

Table 6 demonstrates the results of weight loss of the sample when determining the duration of fire protection of wood.

As Table 6 indicates, fire-proof wood sample treated only with organo-inorganic coating after 60 cycles of testing lost a considerable amount of flame retardants, which led to a weight loss of more than 9% during fire exposure, but the hydrophobiser based on alkyd-polyurenitan varnish provided resistance to fire-proof coating during cyclic tests of about 120 cycles, hydrophobised capillaries and microcracks of the surface, forming a complex water-repellent protective layer, and increasing the thermal resistance of the formed composites.

Table 6. Results of sample weight loss when determining the duration of wood fire protection

Wood sample	Number of test cycles	Average weight of the sample before fire protection, g	Average sample weight, g		Sample mass loss, %
			Before	After	
			Tests		
Treated with an organo-inorganic coating	Control	131.1	144.3	133.9	7.2
	4	132.6	145.9	134.1	8.1
	16	136.8	150.3	138.8	7.6
	28	126.2	138.1	126.1	8.7
	42	125.1	136.7	125.6	8.1
	60	125.8	138	126.4	8.4
	68	135.0	145.8	131.2	9.8
	72	137.4	148.1	134.2	9.4
Organo-inorganic coating with hydrophobiser based on alkyd-polyurenitan varnish	control	132.0	144.2	131.9	8.5
	20	126.9	139.7	127.5	8.7
	40	135.3	147.5	135.1	8.4
	80	130.2	142.1	129.6	8.7
	120	132.1	143.2	128.5	10.2

As a result of the computer solution, regression equations were obtained and ternary surfaces were constructed depending on changes in variation factors (Fig. 5). Regression equation:

$$Y_{calc} = 8.648 + 0.767X_1 - 1.2X_2 + 0.911X_{11} - 0.989X_{22} - 0.0001X_1X_2 \quad (2)$$

Based on the conducted computer modelling, the best value of the number of test cycles and the protective coating that ensures the performance of the task was determined, namely the lowest value of the material mass loss.

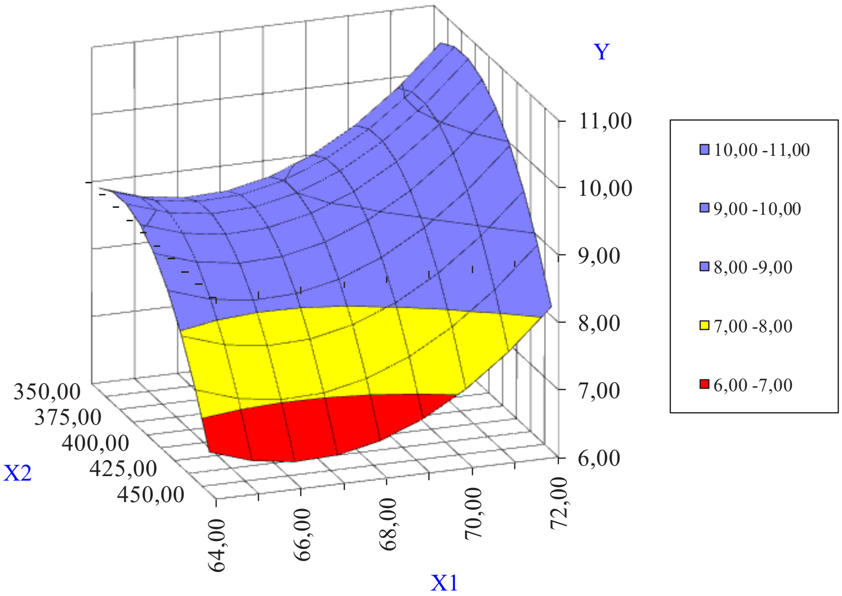

Figure 5. Ternary surfaces of changes in the output parameter depending on changes in variation factors

Discussion

Thus, a change in the fire-hazardous properties of wood upon fire protection has been established. Under the influence of a high-temperature flame and the composition of the coating, as indicated by the results of studies (Table 3, Figs. 3, 4), there is a natural process of reducing the flammability of wood. This is conditioned upon the mechanism of operation of the coating, which lies in the formation of a layer of foam coke, which slows down the heat transfer processes. Notably, protection from fire by the coating leads to the formation of a foam layer on the wood surface and, accordingly, reduces access to combustible components. It is this mechanism of action on wood that serves as a factor in regulating the degree of protection against fire, as well as the effectiveness of water protection of fire-proof wood. Therewith, this mechanism adversely affects the smoke-forming ability of the coating when protected by alkyd-polyurethane varnish. This coincides with the data of the studies [4; 10], where developers also associate changes in the smoke formation process with processing with organic components. In contrast to the results given in [5; 7], the results obtained in this paper suggest the following:

– the main regulator of the reduced heat insulation of wood is not only the formation of a foam layer, but also the thermal resistance of the fire-resistant coating;

– a substantial impact on the transition of wood from a combustible material to a group of materials that burn slowly and slow down the spread of flame by a surface with a low smoke-forming ability is carried out due to treatment with fire-resistant coatings.

Results of improving the performance characteristics of wood protected from fire under the action of a coating based on alkyd-polyurenitan varnish and the formation of a hydrophobic layer (Tables 4, 5) indicate an unambiguous effect of protection with the formation of a strong and dense hydrophobic protective layer on the surface of the material. This uncertainty cannot be resolved in this study, as it requires large-scale experiments to obtain more reliable data. Based on these results, one can state the existence of an interesting pattern associated with the formation of heat resistance to flame and an ability to insulate wood while ensuring effective fire protection.

Conclusions

A study of the fire-hazardous properties of wood with fire-resistant coatings during the formation of a heat-insulating layer of coke was carried out, the mechanism was determined and a change in indicators for fire protection was obtained, which allowed justifying the effectiveness of a fire-resistant coating under the influence of temperature. Tests on model samples of fire-proof wood showed that coatings under the influence of elevated temperatures form a swollen layer of foam coke, contributing to thermal insulation of the wood surface, and preventing the elevated temperatures from reaching the wood and its subsequent burnout. This slows down the smoke formation and combustion of the material. In general, the effectiveness of fire protection of wood, which was obtained by the multifactorial method of determining the operational properties, established that the treated wood belongs to non-flammable materials that slowly spread the flame over the surface and have a low smoke-generating capacity.

The legality of the joint use of hydrophobisers with a fire-resistant coating of wood on particular models of the influence of changes in humidity and temperature was confirmed. Conducted studies on the determination of the degree of hydrophobisation of wood, the corrosive effect of protective agents on metals and the duration of fire protection of wood by keeping them at variable temperature and humidity indicators within wide limits showed that when applying a hydrophobiser, a waterproof layer is formed, which protects wood from the action of moisture and the washing out of flame retardants, namely the capillaries and microcracks of the surface are hydrophobised by a protective polymer film, which increases operational performance.

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Багатофакторний метод оцінювання ефективності вогнезахисту деревини

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Анотація. Проблема застосування вогнезахисних матеріалів для дерев'яних будівельних конструкцій полягає в забезпечені їх стійкості і довговічності при експлуатації в умовах атмосферного коливання, коли можливе вимивання антипіренів і втрата вогнестійкості. Мета проведених досліджень полягає у визначені показників пожежної небезпеки деревини, вогнезахищеними покриттями та вплив на них утвореного тепло ізолюючого шару коксу, що дозволяють обґрунтувати ефективність вогнезахисного покриття при впливі температури. В роботі використано комплексний метод дослідження, що полягав у визначені пожежонебезпечних властивостей вогнезахищеної деревини та методів визначення експлуатаційних властивостей при вогнезахисті деревини. Встановлено, що при застосуванні покриття на основі алкід-поліуренітанового лаку, за рахунок утвореної полімерної плівки на поверхні деревини зменшується проникність компонентів антипірену. Випробування пожежонебезпечних характеристик захисту деревини від вогню показали, що покриття під впливом дії теплового потоку спучується та сприяє утворенню значного тепло-ізолювального шару коксу, який запобігає проходженню до деревини кисню та відповідно високої температури, яка здатна запалити деревину. Загалом ефективність захисту деревини від вогню, показала, що деревина захищена від вогню відносяться до важкогорючих матеріалів, які повільно поширюють полум'я поверхнею з малою димоутворювальною здатністю. Практична цінність полягає у тому, що отриманий метод визначення характеристик захисту деревини від вогню, полягає у визначені як атмосферних, так і термічних властивостей, та уможливлює встановлення умови експлуатації вогнезахисту та застосування виробів і будівельних конструкцій з деревини широкого спектру використання

Ключові слова: захисні засоби, втрата маси, оброблення поверхні деревини, вимивання антипірену, полімерна оболонка